

Comparison of images obtained from a 2D Gulf of Mexico subsalt dataset using different migration approaches

Michael Fehler*, Lian-Jie Huang, Doug Alde, Steve Hildebrand, Los Alamos National Laboratory

Charles Burch, Conoco, Inc.

Summary

During the past few years, there has been interest in developing migration approaches that provide more reliable images of complex regions than can be obtained using the Kirchhoff approach while at the same time maintaining some of the computational speed of the Kirchhoff method. As part of that effort, we have been investigating a suite of migration methods that are implemented in the wavenumber and space domains and operate on data in the frequency domain. The best known example of these methods is the split-step Fourier method (SSF). Two of the methods that we have developed are the Extended local Born Fourier (ELBF) migration approach and the extended local Rytov Fourier (ELRF) migration approach. We compare the migrations obtained using the SSF, SSF with multiple reference slownesses, ELBF, ELRF, and the Kirchhoff approach on a 2D field dataset collected over a salt body in the Gulf of Mexico.

Introduction

With increased emphasis on finding petroleum in regions of complex structure, there is increased interest in finding migration methods that are both fast and more reliable than the Kirchhoff approach. We have been investigating a suite of migration methods that are implemented in the wavenumber and space domains and operate on data in the frequency domain. The best known example of these methods is the split-step Fourier method (Stoffa et al. 1990). Two methods that we have developed, whose implementation procedure is similar to that of the SSF method are the extended local Born Fourier migration approach (Huang et al. 1997) and the extended local Rytov Fourier migration approach (Huang et al., 1998). Both of these new methods use approximations that are less restrictive than the conventional SSF approach and tests using numerical data for the SEG/EAGE salt model and the Marmousi model demonstrate that they give better images than those obtained using the SSF approach (Huang et al. 1997; Huang et al. 1998). In addition to the methods themselves, we have investigated implementation issues such as the use of the multiple reference velocity approach introduced by Kessinger et al. (1992) into the SSF approach to limit the velocity perturbation and thus improve the reliability of the images obtained (Huang and Fehler, 1997; Huang et al. 1997).

To date, we have reported on tests of these methods using numerical data. After a brief introduction to the methods, we

will compare the images obtained from migrating a 2D field dataset collected over salt in the Gulf of Mexico. We will compare images obtained by the various dual-domain methods with the image obtained using a Kirchhoff migration algorithm. We will also discuss the relative computing cost of the methods.

Split-step Fourier method

The constant density scalar wave equation in the frequency domain is

$$\left[\frac{\partial^2}{\partial x^2} + \frac{\partial^2}{\partial y^2} + \frac{\partial^2}{\partial z^2} + \frac{\omega^2}{v^2(\mathbf{x}_T, z)} \right] p(\mathbf{x}_T, z; \omega) = 0$$

where $\mathbf{x}_T \equiv (x, y)$; $p(\mathbf{x}_T, z; \omega)$ is the pressure in the frequency domain, $v(\mathbf{x}_T, z)$ is the velocity of the medium, and ω is the circular frequency. The split-step Fourier approach is a one-way wave propagation method that is based on the use of a small angle approximation to arrive at an algorithm for propagation across layers perpendicular to the main propagation direction using the following propagator

$$p(\mathbf{x}_T, z_{i+1}; \omega) = p_0(\mathbf{x}_T, z_i; \omega) e^{i\omega \int_{z_i}^{z_{i+1}} \Delta s(\mathbf{x}_T, z) dz}$$

where $p_0(\mathbf{x}_T, z_i; \omega)$ is the wavefield at z_i obtained by propagation of the wavefield at z_i across the interval Δz where the interval is assumed to have homogeneous velocity v_0 and

$$p_0(\mathbf{x}_T, z_{i+1}; \omega) = F_{\mathbf{k}_T}^{-1} \left\{ e^{ik_{0z}\Delta z} F_{\mathbf{x}_T} \{ p(\mathbf{x}_T, z_i, \omega) \} \right\}$$

where $k_{0z} = \sqrt{k_0^2 - \mathbf{k}_T^2}$, $\mathbf{k}_T = (k_{0x}, k_{0y}, 0)$, $k_0 = \omega / v_0$ and $F_{\mathbf{x}_T}$, $F_{\mathbf{k}_T}^{-1}$ are 2D Fourier and inverse Fourier transforms over \mathbf{x}_T and \mathbf{k}_T , respectively. The split-step Fourier propagator is applied to data in the frequency domain. Propagation is done in two steps: a free space propagation in the wavenumber domain across each depth interval using the background slowness for the interval s_0 followed by a correction for the heterogeneity described by Δs within the propagation interval, which is done in the space domain. The heterogeneity Δs is assumed to be small. The wavefield is transferred between the space and wavenumber domains using a Fast Fourier Transform. Since the propagator depends only on the local properties of the medium, one

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would not have to have access to the entire velocity structure of a model to propagate through a portion of the model. This gives the method a great computational advantage over some other wave-equation based methods.

Extended local Born Fourier propagator

The extended local Born Fourier method is based on an application of the Born approximation within each layer in the model. Huang et al. (1997) showed that the propagation equation is

$$p(\mathbf{x}_T, z_{i+1}; \omega) = p_0(\mathbf{x}_T, z_{i+1}; \omega) + p_s(\mathbf{x}_T, z_{i+1}; \omega)$$

where

$$p_s(\mathbf{x}_T, z_{i+1}; \omega) = i\omega\Delta s(\mathbf{x}_T, z_i)\Delta z \cdot F_{\mathbf{k}_T}^{-1} \left\{ \frac{k_0(z_i)}{k_z(z_i)} e^{ik_z(z_i)\Delta z} F_{\mathbf{x}_T} \{p(\mathbf{x}_T, z_i; \omega)\} \right\}$$

Huang et al. (1997, 1998) discussed a computational approach for dealing with the possibility that $k_z(z_i)$ is equal to or nearly equal to zero. Huang et al. (1997) show that the extended local Born Fourier propagator reduces to the split-step Fourier propagator for the case of small perturbation and small propagation angle.

Extended local Rytov Fourier propagator

The extended local Rytov Fourier method is based on an application of the Rytov approximation within each layer in the model. The method is discussed by Huang et al. (1998). The propagation equations are

$$p(\mathbf{x}_T, z_{i+1}; \omega) = p_0(\mathbf{x}_T, z_{i+1}; \omega) e^{i\omega \left[\int_{z_i}^{z_{i+1}} \Delta s(\mathbf{x}_T, z) dz \right]} \chi(\mathbf{x}_T, z_{i+1}; \omega)$$

where

$$\chi(\mathbf{x}_T, z_{i+1}; \omega) \equiv p_1(\mathbf{x}_T, z_{i+1}; \omega) / p_0(\mathbf{x}_T, z_{i+1}; \omega)$$

and

$$p_1(\mathbf{x}_T, z_{i+1}; \omega) = F_{\mathbf{k}_T}^{-1} \left\{ \frac{k_0(z_i)}{k_z(z_i)} e^{ik_0(z_i)\Delta z} F_{\mathbf{x}_T} \{p(\mathbf{x}_T, z_i; \omega)\} \right\}$$

As discussed by Huang et al. (1998), the extended local Rytov Fourier approach is more stable than the extended local Born Fourier approach, handles amplitudes more correctly than either the SSF or ELBF approaches and gives better images when migrating numerical datasets.

Multiple reference slowness approach

Kessinger et al. (1992) introduced the concepts of using multiple reference slownesses into the SSF method. Since the SSF method is more reliable when the lateral slowness perturbation within a given extrapolation interval is small,

the interval is broken into a number of sections, the average slowness in each section is used as a reference slowness, and the wavefield is extrapolated across that section using that slowness. Huang et al. (1997) show that the multiple reference slowness approach helps to stabilize the otherwise unstable ELBF method when migrating data in regions having large lateral slowness contrasts. Without the multiple reference slowness approach, the ELBF method cannot be applied to datasets such as the one for the SEG/EAGE salt model.

Kirchhoff migration approach

We perform Kirchhoff migration using first arrivals calculated using a 3D eikonal code written by Fei et al. (1995). To calculate traveltimes for the 2D model, we stack a set of the 2D models to simulate a 3D region. The migration is done by summing the time delayed and weighted contributions from a set of seismic traces at a particular image point below the earth's surface. Each trace has an associated surface source and receiver location. We assume that a single ray path (the first arrival ray path) connects the surface point and the image point. Therefore this method assumes that the image point is not in a shadow zone, not a caustic (a multiple ray path event), and that first arrival ray path has sufficient reflection energy.

Dataset

The dataset is a 2D prestack dataset provided by Conoco. The dataset consists of 692 shots having 240 receivers each with 2501 time samples at 0.004s. The image volume we migrated into had dimensions of 1024 in x by 900 in z with grid a spacing of approximately 25 m horizontally and 10.1 m vertically. Shot spacing is 37.5 m and receiver spacing is 25 m. Figure 1 shows a portion of the model. The region in the upper right hand portion of the model is a salt body that extends off the right. The left hand edge of the salt body is at

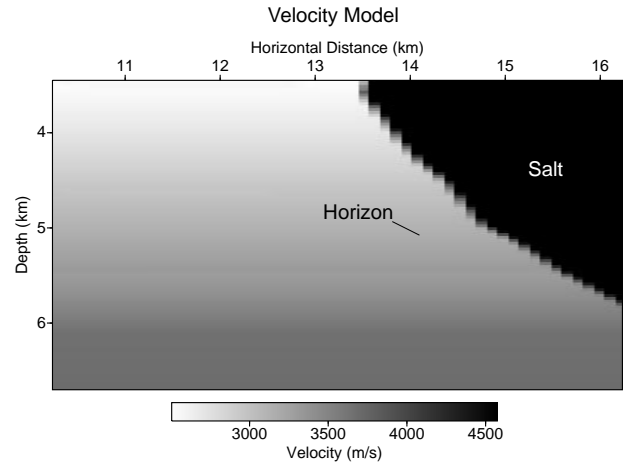


Figure 1. Portion of velocity model used for migration.

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approximately $x=13\text{km}$; $z=3\text{km}$. According to interpretations of 3D images, the region of the model shown in Figure 1 has little out-of-plane structure so it provides a good region to test 2D migration.

Results

For migrations using the SSF, ELBF and ELRF methods, we used a 15 Hz Ricker source and migrated over a frequency range of 5-45 Hz. Figures 2-6 show the results of the migrations. Figure 2 shows the result obtained using the first-arrival Kirchhoff scheme, Figure 3 shows the result of using the SSF method, Figure 4 shows the result of using the split-step Fourier method with multiple reference slownesses, Figure 5 shows the result obtained using the extended local Born Fourier method with multiple reference slownesses, and Figure 6 shows the results from using the extended local Rytov Fourier method. Note in particular the region beneath the salt labeled “horizon” in Figure 1.

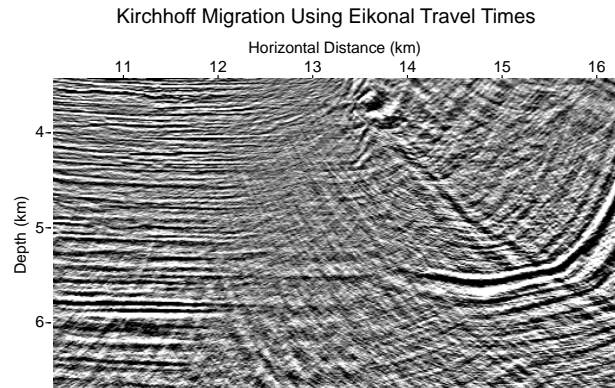


Figure 2. Image obtained using Kirchhoff migration of the region shown in Figure 1.

In the Kirchhoff image, the zone beneath the salt is completely washed out except for a high amplitude event that crosses the salt boundary. Since most of the first-arrival energy in this region is in the form of head waves generated at the edge of the salt body located just above the region shown in the figure, the Kirchhoff migration does not give a good image. From finite difference modeling of the forward wavefield, we find that the large amplitude event is parallel to a refracted wave wavefront. The layered structures in the left portion of the image show good continuity but the continuity is lost in the region beneath the salt. The base of salt is well-positioned by the Kirchhoff method; however, note that the velocity model for this dataset was constructed using Kirchhoff migration to iterate towards a model, thus, the agreement between the Kirchhoff image and the location of the base of salt in the velocity model is not surprising.

In the SSF image, Figure 3, the continuity of horizons seen in the left portion of the figure continues a little beneath the salt. There is evidence for some horizons beneath the salt

but they do not appear to be flat but have a concave upwards appearance, indicating that they are artifacts of the migration. The high amplitude event that appears in the Kirchhoff image is also visible in the SSF image. The use of multiple reference slownesses with the SSF method appears to give better definition of horizons beneath the salt but they are all concave upwards as shown in Figure 4. The base of salt appears to be a more crisp event in the SSF with multiple reference slownesses.

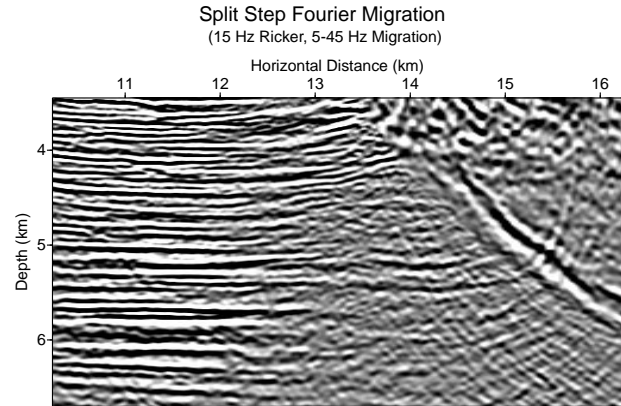


Figure 3. Image obtained using SSF migration method.

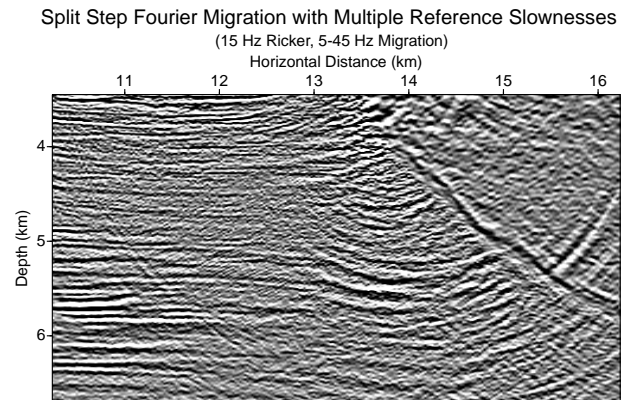


Figure 4. Image obtained using the SSF method with multiple reference slownesses.

The ELBF method with multiple reference slowness method gives an image, Figure 5, that is comparable to the SSF with multiple reference slownesses. While the ELBF method works quite well with zero-offset numerical data (Huang et al., 1997), it does not do so well with real prestack data.

The image obtained using the extended local Rytov method, Figure 6, has events that begin on the left hand side of the image, away from the salt and continue beneath and almost up to the salt boundary. The high amplitude event that was visible in the Kirchhoff image is also present but its amplitude is much lower than in the other images. The lower

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salt boundary is well positioned. Of particular interest is the one nearly-horizontal event located at a depth of about 5.2 km that is very clear beneath the salt. On the SSF and ELBF images, this horizon appeared to be concave up beneath the salt. On the ELRF image, the event shows good continuity with a little increase in depth beneath the salt.

The computing times for the application of the SSF and ELBF methods to the entire dataset are approximately five to 7 times those of the Kirchhoff method. The ELBF method has one more Fourier transform over the horizontal dimension for each extrapolation step than does the SSF method. However, the SSF method has an extra complex multiplication at each horizontal grid location than does the ELBF method. This complex multiplication is slower than the additional Fourier transform required by the ELBF method so the SSF requires slightly more computing than the ELBF method. The ELRF method requires one additional Fourier Transform than the SSF so it takes approximately 30% more computing than the SSF method.

Local Born Fourier Migration with Multiple Reference Slownesses
(15 Hz Ricker, 5-45 Hz Migration)

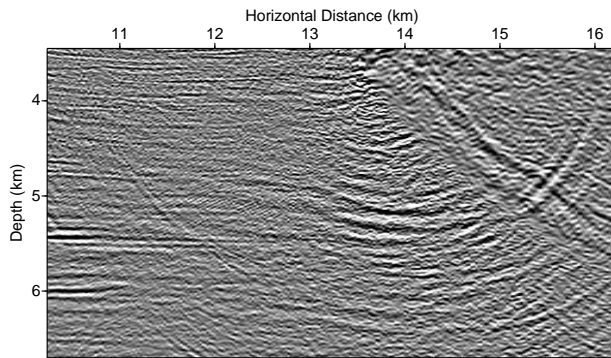


Figure 5. Migration image obtained using extended local Born Fourier migration method with multiple reference slownesses.

Local Rytov Fourier Migration with Variable Depth Intervals
(15 Hz Ricker, 5-45 Hz Migration)

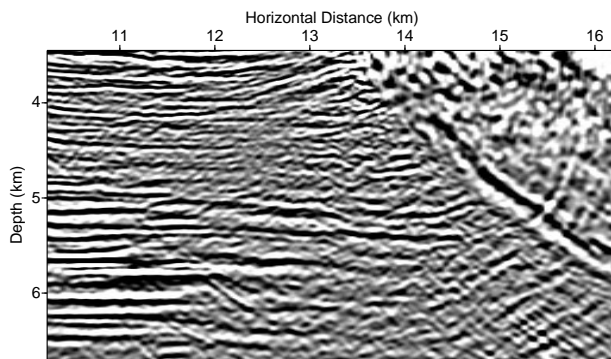


Figure 6. Migration image obtained using extended local Rytov Fourier migration method.

Conclusions

We have compared migration images obtained from migrating a subsalt prestack dataset using five methods, the first-arrival Kirchhoff migration, split-step Fourier, split-step Fourier with multiple reference slownesses, extended local Born Fourier method with multiple reference slownesses, and the extended local Rytov Fourier methods. We have found that the image obtained with the extended local Rytov Fourier method is superior to the one obtained by the other methods. It provides more information about strata beneath the salt and the events beneath the salt are more consistent with those away from the salt. Some of the horizons continue up almost to the salt in the image we obtained.

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